Fluid-Escape Structures in the Subsurface: Minimum Flow Velocities of Pressure-driven Slurry Injection during Natural Hydraulic Fracturing

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Abstract

Field studies of natural hydraulic fractures and fluid-escape structures yield data on the maximum clast size observed at each outcrop, data that were then used to constrain the minimum flow velocity of the sediment slurry injected into a hydraulic fracture during a fluid-escape event. Because grain concentrations at the time of injection are not recorded in rock outcrops, flow velocities were examined over a range of reasonable grain concentrations to evaluate the velocities necessary to carry the largest observed clasts as grain concentration varied. Analysis of the data revealed several tends in fluid-escape structures: 1) Most injectites have maximum clast sizes below 30 cm and most slurries have minimum flow velocities < 3 m s^{-1}, 2) As the concentration of suspended particles increases, dependence on flow velocity decreases, and 3) As maximum clast size decreases below several centimeters, dependence on flow velocity greatly decreases. Although these trends in the data result from field observations, the effects of the numerical methods also cannot be ignored. This study represents a first attempt to evaluate the roles of maximum clast size versus grain concentration in estimating the minimum flow velocity for an escaping fluid slurry.

Introduction

Hydraulic fracturing is the result of fluid pressures in a porous medium exceeding the strength of the rock medium. In the rock record evidence of hydraulically induced fractures appears as a series of sedimentary veins, dikes and sills, often called injectites, because a fluidized sediment slurry was injected into the fractures as they opened. The conditions and rock types in which these injectites form vary among location as a result of different tectonic settings, sediment or rock types, stratigraphy, grain-size distributions and fluid types. Hydraulic fracturing, and its associated fluid-escape structures, is well recognized in the rock record.

Numerous publications on fluid-escape structures document field examples of hydraulic fractures with injectites in nature (Sherry et al. 2012; Hubbard et al. 2007; Hannum 1980; Scott et al. 2009) and provide data on the sizes, geographic frequency, and characteristics of injectites. One pressing question is how fast the slurry was flowing in order to inject sediment into the fracture. The goal of this study is to constrain the minimum flow velocity during injection events using the largest clasts that were transported by the flowing slurry. Maximum clast size reported from outcrop observations can be used to calculate a settling velocity, which is then translated to the minimum velocity required to transport the largest clast in a flowing slurry. Methods for computing settling velocities vary among studies, so the published velocities are often not directly comparable (Ross et al. 2014; Duranti & Hurst 2004; Allen 1985). In order to give a sound overview of injectites, it was necessary to merge the methods used to compute settling velocities, allowing for comparison of the observed fluid-escape structures. Because the concentration of fine grains in the slurry at the time of injection is not recorded in outcrop, flow velocities were examined over a range of reasonable grain concentrations to evaluate the velocities necessary to transport the observed largest clasts.

*Figure 1 – Field examples of hydraulic fractures with injectites. **A**. Brown sand-filled vertical dike filling hydraulic fracture running along the left side of the gully (to the left of the 15 cm notebook) that was injected into 50 million year old, horizontally layered grey shale, Svalbard. **B.** Vertical hydraulic fracture with boulders injected into 30,000 year-old siltstone, China. Yellow scale bar is 30 cm. From Dechen et al., 2013.*

By examining multiple injectite sites (e.g. Figure 1) and using a common theoretical basis, it was possible to investigate the range of flow velocities associated with sediment injection. This type of analysis represents a step towards understanding the occurrence of injectites globally.

Methods

This research project was part of the Undergraduate Research Opportunities Program (UROP) at the University of Minnesota. I found the feedback provided by a faculty mentor allowed for sound progress to be made, despite the semester-length limitation.

Literature Review

As with most research, this project began with a review of the existing literature available on fluid-escape structures, injectites and the dynamics of slurry flows from two disciplines, Geology and Engineering. The Geology literature focused on field examples of injectites, explored grain-size distributions, spatial relations of mud dikes to one another, etc. thus providing a solid basis as to how these events are recorded in the field (Hannum 1980; Vigorito & Hurst 2010; Davies 2003). Additionally, the geologic literature provided some context of the events, such as tectonic setting, stratigraphic relations, and other data useful for resolving the forces that drive these events (Goulty 2008; Cartwright et al. 2003). However, in spite of the wealth of descriptive data provided by the geologic literature, authors did not often provide thorough analyses of the dynamics of slurry flows.

The Engineering literature helped to bridge the gap by providing a more thorough exploration of the physics behind solid particles suspended in a flowing slurry. Due to the practical nature of engineering, its associated literature was necessarily focused on the application of physics to real world problems. For example, one author describes the dynamics of vertical and inclined slurry flows, but only gives equations to calculate the pumping pressures needed in order to sustain movement (Wilson et al. 2006). The engineering literature proved to be informative on many fronts, but did not provide a method to infer flow velocity that would be useful for this project.

Through continued review of the literature, sedimentologic approaches were found to be extremely applicable to the goals of this project. Taking the principles established by physicists, observations made by field geologists and some experimentation, sedimentologists have derived methods by which the quantification of slurry-flow velocities is possible (Allen 1985; Di Felice 2010). These methods would allow for the calculation of flow velocities based on the observations made by field geologists. In order to minimize errors, it was necessary to employ a single computational method to the field observations from the literature to allow for direct comparison among field sites. Otherwise, if published settling velocities are copied directly from studies with different methods of flow-velocity calculation, flow velocities would not be comparable as each method relies on its own set of assumptions. The next step was to apply the numerical approaches from sedimentology to a suite of field examples in order to get a sense of the scale of flow velocities operating in hydraulic fracturing events.

Basic Calculations

The first method derives from volcanology and is used to estimate a magma's rate of ascent based upon the observed maximum size of xenoliths in igneous intrusions (Spera 1984). The following equation was applied:

$$U_n = 0.344\left(\frac{\Delta\rho g}{\rho_l}\right)^{\frac{5}{7}}\left(\frac{\rho_l}{\eta_l}\right)^{\frac{3}{7}}\left(R_n - \frac{15\sigma_0}{4\Delta\rho g}\right)^{\frac{8}{7}} \tag{1}$$

Table 1. Parameters for Eq. (1) when applied to sandstone clasts in freshwater.

U_n	clast settling rate (m s^{-1})
ρ_n	clast density (kg m^{-3}) = 2500 kg m^{-3}
ρ_l	fluid density (kg m^{-3}) = 1000 kg m^{-3}
$\Delta\rho$	$\rho_n - \rho_l$ (kg m^{-3})
η_l	fluid viscosity (Pa s) = 8.90 x 10^{-4} Pa s
g	acceleration due to gravity (m s^{-2}) = 9.81 m s^{-2}
R_n	maximum observed clast radius (m)
σ_0	fluid yield strength (N m^{-1}) = 6.00 x 10^{-5} N m^{-1}

As a starting point, Eq. 1 was used to determine the settling velocity of a pebble, with a radius of 5 mm, in fresh water at room temperature. A clast settling rate of 394.2 m s^{-1} emerged (Table 4). This velocity seems violently high, but given the assumptions of clean water (no silt or mud component), spherical clasts, and laminar flow, it is not unreasonable. When hydraulic fracturing events occur, lithified rock units can be blown apart by the moving slurry, resulting in large angular clasts of rock found in outcrops of injectites and suggesting high flow velocities (Hannum 1980; Hubbard et al. 2007). In order to verify the accuracy of this result another method to calculate settling velocity was needed.

Although Stokes' Law can be used to calculate settling velocity, it was dropped due to the fact that Stokes' Law is inappropriate for clast sizes larger than 100 microns and can overestimate settling velocity by a factor of ten or more (Duranti & Hurst 2004). Therefore yet another method was needed that would allow for the many variables of a hydraulic fracturing system.

Choosing a Method

For a theoretical method to calculate minimum settling velocity to be applied reliably to an injectite, it must account for the following: 1) a large range of clast sizes (tens of microns to tens of centimeters), 2) grain shape, 3) a fluid that contains grains, mud or silt-sized, in suspension with a resultant higher bulk density, and 4) the ability to simulate complex flow regimes.

Ross et al. (2014) studied a series of columnar injectites and performed a detailed analysis of the flow regime during sand injection using a recent numerical method by (Di Felice 2010) that satisfies aforementioned criteria. Di Felice (2010) method is highly sophisticated but requires numerous input data based on a detailed knowledge of a particular injectite. For example, the grain concentration required as an input variable in the Di Felice (2010) computation proves problematic, for no reliable method exists to determine grain concentration from outcrop evidence. In order to apply a single method to a large number of field sites and compare field sites, it became necessary to find a method that balanced accuracy and flexibility.

The method of Duranti and Hurst (2004) became the method of choice for this study, as it fit the necessary criteria outlined above and has been used successfully in other injectite studies (Sherry et al. 2012; Vigorito & Hurst 2010). Unlike the Di Felice (2010) method, Duranti and Hurst's equation relies upon features easily observed in the field combined with relations well-constrained by laboratory data. For the purposes of this study, Duranti and Hurst's method of calculating minimum settling velocity proved to be much more effective:

$$V_{mf} = k\left(\frac{\rho_s - \rho_f}{\rho_f} gD\right)^{1/2} \qquad (2)$$

Table 2. Parameters for Eq. (2)

V_{mf}	settling velocity of the largest clasts (m s^{-1})
k	$\frac{4}{3}C_D$, drag coefficient
C_D	0.45, approximate value valid for a large range of Reynolds' number (Duranti & Hurst 2004)
ρ_s	clast density (kg m^{-3}) = 2500 kg m^{-3}

ρ_f	fluid density (kg m^{-3}) = 1000 kg m^{-3}
ρ_{pf}	pseudo-fluid density (kg m^{-3}) = (grain concentration)(ρ_s) + (1 - grain concentration)(ρ_f)
g	acceleration due to gravity (m s^{-2}) = 9.81 m s^{-2}
D	maximum observed clast diameter (m)

MATLAB

In order to visualize the effects of clast size in a slurry with bimodal grain sizes, a computer method was necessary to handle the calculations. Matlab was used to model a flowing slurry with large clasts (typically the only variable) transported in a mixture of water with mud and silt-sized grains in suspension. Matlab was preferred for two reasons. The flexibility of programming inherent to Matlab allowed for the boundaries of the simulation to be adjusted quickly and easily. In addition, powerful graphing tools allowed for easy interpretation of the data.

The published literature on injectites provided several field sites from which the maximum grain size had been recorded. The Duranti and Hurst (2004) method (Eq. 2) was applied to a wide range of field measurements. The maximum grain size is a useful statistic as it gives the minimum velocity of the flow necessary to move the largest clast upward (Duranti & Hurst 2004). If the velocity of a flowing slurry was any less than the settling velocity of the largest clast, the clast would have not been emplaced.

The bulk density of a slurry also has an effect on the flow velocity required to move the largest clasts. If a moving slurry contains suspended particles smaller than the maximum clasts, one is allowed to treat the combination of small suspended grains and the ambient fluid as a pseudo-fluid (Di Felice 2010). So any material, such as very fine particles, organic debris or gases in the moving slurry, changes the bulk density of the fluid. By simplifying a multi-phase system to a two-phase system consisting of the largest clasts suspended in a pseudo-fluid with smaller suspended grains, it is possible to simplify this complex system. The last variable input into Matlab was a range of plausible grain concentrations, which represents the fraction of non-fluid material in the slurry. Grain concentration and bulk density are linked, so if the concentration of small grains suspended a slurry increases, so does the bulk density of the flowing slurry.

The powerful graphing functions of Matlab allowed a 3D plot of the above variables to be generated. The main variable, the maximum observed clast size for each field site, was used in conjunction with a range of inferred grain concentrations. The final step involved programming a Matlab script which would calculate a settling velocity using Eq. 2 and display the results as a 3D surface, with each input field site plotted on the surface (Figure 2). Because the settling velocities are equal to minimum flow velocities required to emplace the observed large clasts, one can then infer a minimum flow velocity during slurry injection, an important element of slurry-flow dynamics.

Discussion and Conclusions

My quantitative method allows for comparison of injectites that were emplaced in natural hydraulic fractures as pressurized pseudo-fluids escaped from the subsurface. A graphic representation of the relationship between largest observed clasts over a range of small-grain concentrations within the escaping pseudo-fluid illustrates trends that have not been previously recognized and provides insight into injectites that is previously unexplored (Figure 2).

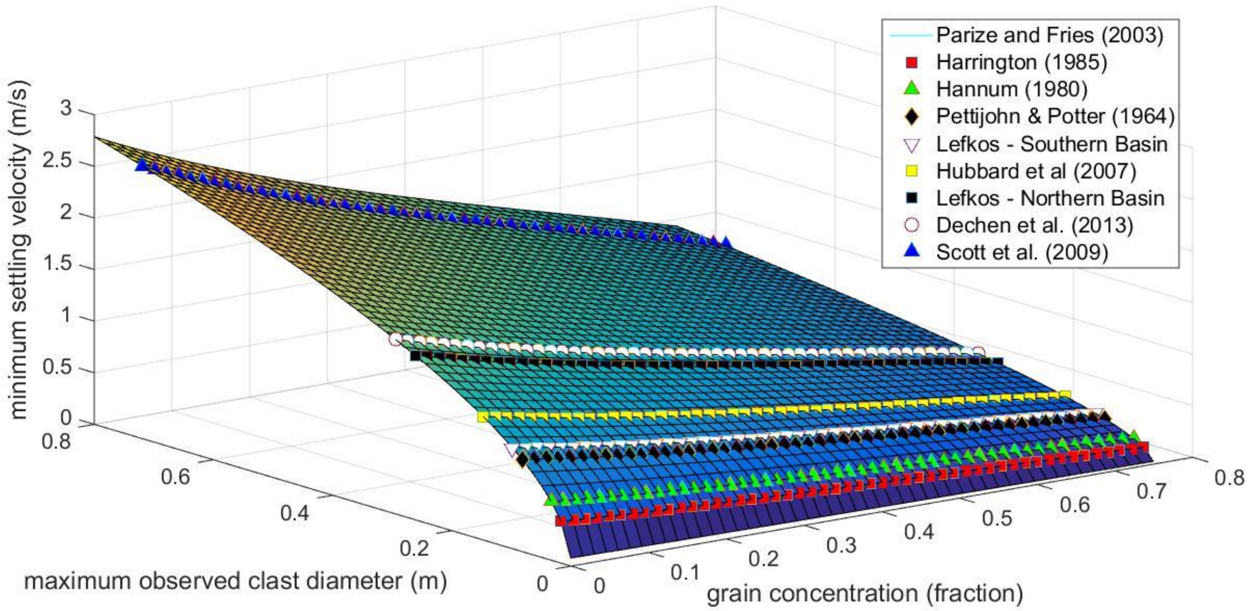

Figure 2 - Colored surface represents the settling velocity for a clast of maximum observed diameter (m) over a range of grain concentration using Eq. 2 applied to a variety of field sites, each of which is denoted by a different symbol. The Northern and Southern Lefkos Basin sites are from unpublished data. Note: The Parize and Fries (2003) curve plots along lower limit of clast size, just above grain concentration axis.

Maximum observed clast diameter refers to the largest single clast observed in a fluid-escape injectite (Figure 1). This clast size is used to calculate the minimum settling velocity (Figure 2), and therefore to infer the minimum flow speed of the escaping sediment slurry. Values used in the construction of Figure 2 are shown in Table 3. Grain concentration refers to the fraction of small particulate matter in the slurry, the solid constituents of the pseudo-fluid. On the grain concentration axis, 0 refers to clear fresh water whereas 0.8 refers to a pseudo-fluid with 80% fine sediment in suspension. The density of the pseudo-fluid is calculated based upon the fraction of grains suspended in the fluid. For example, a grain concentration of 0.6 would be 40% water and 60% grains. The density of the grains is the same as the density used for the clasts, and was chosen to reflect the density of sandstone, which is a common host rock of fluid-escape structures.

Minimum settling velocity is plotted as a surface. Each field site is represented by a curve of shapes along which each shape is the intersection point on the surface where the settling velocity was calculated, and the curve represents the range of velocities possible at each field site. The line for each field site spans the entire range of grain concentrations because no reliable means exists to determine the grain concentration at the time of injection. Not only may finer grains remain entrained in the moving flow as the largest clasts become stationary and are deposited, but fluid-escape structures remain conduits for fluid flow long after their formation (Ross et al. 2014), so small grains may be transported away post-depositionally.

The drag coefficient in Eq. 2 (C_D) has been held constant across the surface in Figure 2. A chosen value of 0.45 was used in calculations. This value is a coefficient used to represent a particle in motion, and accounts for the interaction between a grain and the fluid. The value of 0.45 is an approximate value valid for a large range of grain shapes and Reynolds' numbers (Duranti & Hurst 2004).

Reference	Page number	Maximum clast diameter observed (m)	Stratigraphic Unit Intruded by Injectites
Dechen et al. (2013)	128	0.30	Quaternary braided fluvial strata, Fangshan District, China
Hannum (1980)	36	0.025	Jurassic Entrada Sandstone, Kodachrome Basin, Utah
Harrington (1985)	195	0.002	Central North Sea, Atlantic Ocean
Hubbard et al.(2007)	204	0.20	Cretaceous Cerro Toro Formation, Magallanes Basin, Southern Chile
Parize & Fries (2003)	63	0.003	Lower Cretaceous Blue Marls Formation, Vocontian Basin, SE France
Pettijohn & Potter (1964)	Plate 113B	0.18	Archean (Huronian) Espanola Formation, Sudbury district, Ontario, Canada
Scott et al. (2009)	571	0.7	Santa Cruz Mudstone, California
Unpublished	N/A	0.25	Plio-Pleistocene northern margin of Lefkos Basin, Karpathos, Greece
Unpublished	N/A	0.09	Plio-Pleistocene southern margin of Lefkos B

Table 3 Data used in the computation and construction of Figure 2; the injectite of Dechen et al. (2013) is shown in Figure 1B.

Several trends are apparent in Figure 2: 1) The larger the maximum clast size, the more sensitive flow velocities are to the concentration of finer grains in the pseudo-fluid; 2) Minimum flow velocity is less dependent on maximum clast size as grain concentration increases, so as more fine material is incorporated into a slurry, larger clasts can be moved at similar flow velocities; 3) As the maximum clast size decreases from the cm- to mm-scale, flow velocities drop exponentially, particularly at very low grain concentrations; and 4) As maximum clast size nears the meter-scale at low grain concentrations, minimum flow velocities increase dramatically. This effect can be seen in the upward concavity of the velocity surface along the axis at 80 cm clast diameter (Figure 2).

Alternatively, some trends visible in Figure 2 may be the result of how Eq. 2 is constructed. As the equation involves taking the square root of the variables, some of the observed concavities may be artifacts of the equation. Because features such as concavity and changes in slope are likely the result of the equation, caution is called for in interpretation as subtle shifts may not be representative of the dynamics of an injectite event. As such, the methods detailed in this paper represent an approximation of a slurry injection event.

Injectites tend to have a maximum clast size that lies below 30 cm (Figures 1, 2). As a result, most slurries have minimum flow velocities < 3 m s^{-1} (Figure 2). However, only the smallest clast sizes can be supported by slow slurries flowing at < 50 cm per second. It follows that large amounts of energy, usually in the form of fluid pressure, must build up in order to induce hydraulic fracturing and slurry injection. As the maximum clast size increases, tremendous amounts of energy are required.

Each method of calculating minimum settling velocity relies on different assumptions and is typically formulated for a specific application. As can be seen in Table 4, the velocities determined by two methods differ vastly by at least an order of magnitude. The calculation for medium-grained sand with a diameter of 0.4 mm corresponds to the sandstone dike in Figure 1A. Notably, Spera (1984) was originally used to calculate the flow velocity of magma, so the method emphasizes a fluid's yield strength and viscosity, which differ considerably among magmas. In contrast, the method of Duranti and Hurst (2004) was formulated to calculate the minimum settling velocity of a grain in clear water whose properties are built directly into the equation, thus utilizing more relevant input variables, such as grain shape, grain density, and fluid density. Therefore, the method of Duranti and Hurst (2004) represents a more reliable method of determining settling velocities for sediment and, consequently, minimum flow velocities for fluid-escape events.

Clast Diameter	5 mm	0.4 mm
Spera (1984)	394.2 m/s	0.12 m/s
Duarnti & Hurst (2004)	0.16 m/s	0.05 m/s

Table 4 - Minimum settling velocity for two clast sizes in freshwater using Eq. 1 of Spera (1984) and Eq. 2 Duranti & Hurst (2004). Fine pebbles are 5 mm diameter whereas 0.4 mm refers to medium grained sand.

This study suggests initial first-order trends in the relationship among flow velocity, concentration of fine grains in an injected slurry and the size of the largest clasts that are transported during hydraulic fracturing and fluid escape. These results may be enhanced by broadening the field data set. A more exhaustive search of the literature would likely yield additional field sites with appropriate data. Increasing the volume of data may allow for subtle trends in the data to become discernible. Because active slurry-injection events are not observed at the Earth's surface, the combination of outcrop observations and numerical analysis can constrain the velocities of subsurface flow during natural hydraulic fracturing.

References

Allen, J.R.L., 1985. *Principles of Physical Sedimentology* 2nd ed., Blackburn Press.

Cartwright, J., James, D. & Bolton, a., 2003. The genesis of polygonal fault systems: a review. *Geological Society, London, Special Publications*, 216(1), pp.223–243.

Davies, R.J., 2003. Kilometer-scale fluidization structures formed during early burial of a deep-water slope channel on the Niger Delta. *Geology*, 31(11), p.949.

Dechen, S., Loon, A.J.T. Van & Aiping, S., 2013. Genesis of an unusual clastic dike in an uncommon braided river deposit. *Journal of Paleogeography*, 2(2), pp.127–137.

Duranti, D. & Hurst, A., 2004. Fluidization and injection in the deep-water sandstones of the Eocene Alba Formation (UK North Sea). *Sedimentology*, 51, pp.503–529.

Di Felice, R., 2010. Liquid-solid suspension theory with reference to possible applications in geology. *Basin Research*, 22(4), pp.591–602.

Goulty, N.R., 2008. Geomechanics of polygonal fault systems: a review. *Petroleum Geoscience*, 14(4), pp.389–397.

Hannum, C., 1980. Sandstone and Conglomerate-Breccia Pipes and Dikes of the Kodachrome Basin Area, Kane County, Utah. *Brigham Young University Geology Studies*, 27(1), pp.31–50.

Harrington, P.K., 1985. Formation of Pockmarks by Pore-Water Escape. *Geo-Marine Letters*, 5, pp.193–197.

Hubbard, S.M., Graham, S.A. & Romans, B.W., 2007. An Outcrop Example of Large-scale Conglomerate Intrusions Sourced from Deep-water Channel Deposits, Cerro Toro Formation, Magallanes Basin, Southern Chile. *AAPG Memior*, 87, p.p 199–207.

Pettijohn, F.J. & Potter, P.E., 1964. *Atlas and Glossary of Primary Sedimentary Structures*, New York: Springer-Verlag, Inc.

Ross, J. a., Peakall, J. & Keevil, G.M., 2014. Facies and flow regimes of sandstone-hosted columnar intrusions: Insights from the pipes of Kodachrome Basin State Park P. Talling, ed. *Sedimentology*, pp.1–29.

Scott, A., Vigorito, M. & Hurst, A., 2009. The Process of Sand Injection: Internal Structures and Relationships with Host Strata (Yellowbank Creek Injectite Complex, California, U.S.A.). *Journal of Sedimentary Research*, 79(8), pp.568–583.

Sherry, T.J. et al., 2012. Emplacement and dewatering of the world's largest exposed sand injectite complex. *Geochemistry, Geophysics, Geosystems*, 13(1), pp.1–17.

Spera, F.J., 1984. Carbon dioxide in petrogenesis III: role of volatiles in the ascent of alkaline magma with special reference to xenolith-bearing mafic lavas. *Contributions to Mineralogy and Petrology*, 88(3), pp.217–232.

Vigorito, M. & Hurst, A., 2010. Regional sand injectite architecture as a record of pore-pressure evolution and sand redistribution in the shallow crust : insights from the Panoche Giant Injection Complex , California. *Journal of the Geological Society*.

Wilson, K.C. et al., 2006. *Slurry Transport Using Centrifugal Pumps* 1st ed., New: Springer Science & Business Media.